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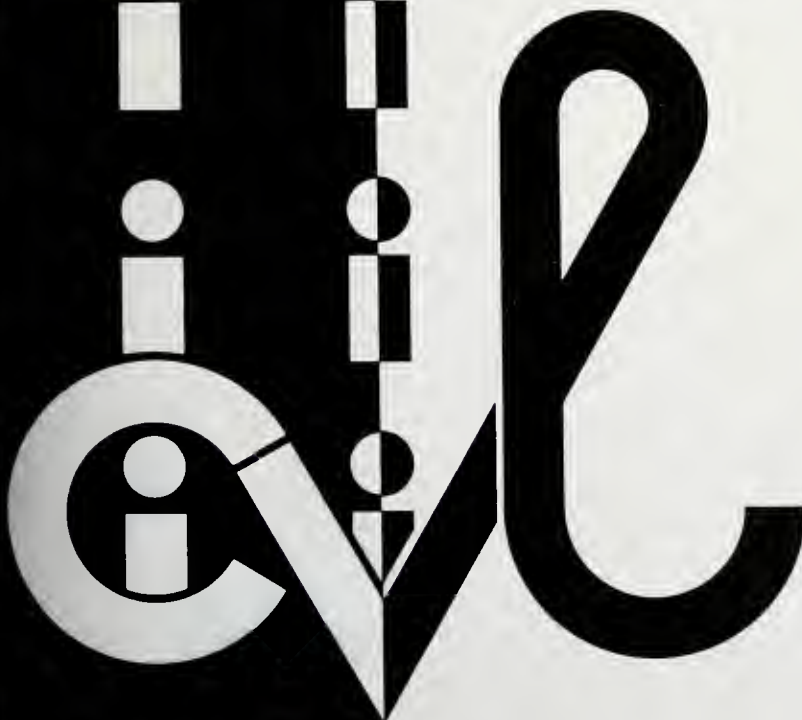
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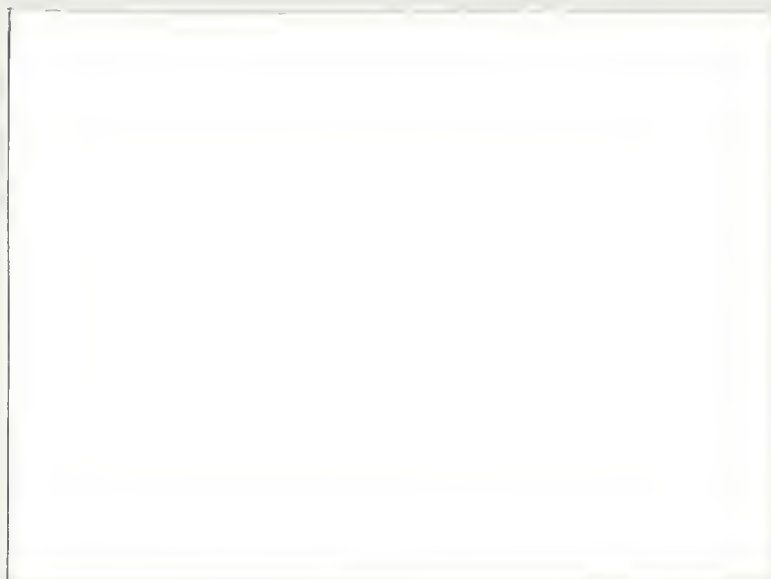
FHWA/IN/JHRP-83/4

AN INVESTIGATION OF RECYCLING  
BITUMINOUS PAVEMENTS

M. Tia  
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PURDUE UNIVERSITY



JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-83/4

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BITUMINOUS PAVEMENTS

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# FINAL REPORT

## "An Investigation of Recycling Bituminous Pavements"

To: Harold L. Michael, Director  
Joint Highway Research Project

March 24, 1983

From: Leonard E. Wood, Research Engineer  
Joint Highway Research Project

Project: C-36-21D  
File: 2-8-4

Attached is the final report for the HPR Research Project "An Investigation of Recycled Bituminous Pavements". The investigations covered in this final report were performed by M. Tia, J. McKinney and A. Iida under the direction of Professors Hancher, Wood and Goetz.

A section of the report covers the effect of different gradations on the behavior of recycled mixtures. This study was added to the final report in response to an oversight in an earlier study.

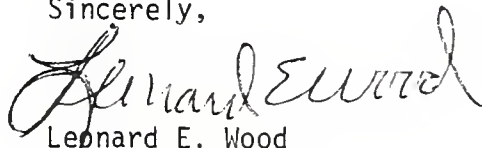
The results of this laboratory study clearly indicate that cold recycling is a very viable construction type that can be used as an accepted rehabilitation technique for upgrading existing worn out asphalt pavements. The extent to which this approach will be used in the future will largely depend upon the various governmental agencies as well as the ingenuity of the contractors.

The four interim reports covered in this final report present the behavior of cold mixed recycled asphalt mixes under a wide variety of circumstances. A suggested design method for cold recycled mixes that uses the gyratory compactor is presented.

An evaluation of the short and long range effects of various rejuvenating agents by means of the creep test is also presented. This procedure developed by Iida shows promise in the rating of the effectiveness of different rejuvenating agents.

This Final Report is submitted for review and approval as fulfillment of the objectives of this project.

Sincerely,



Leonard E. Wood  
Research Engineer

LEW:am

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16. Abstract Interest in cold-mixed in-place recycling of asphalt pavements is becoming more widespread. This final report summarized the findings of four major studies conducted over a period of 5 years. Guidelines were developed that would enable the paving engineer to determine if an existing pavement was a candidate for certain recycling methods and to assist the construction engineer in implementing the recycling method previously identified. The effects of amount and type of added binder(AE-150, AE-90, MC-3000 and AC2.5), amount of added moisture, added virgin aggregate, the compactive effort and curing time on the behavior of cold-recycled asphalt mixtures were studied. A creep test was used to evaluate the long range behavior of recycled mixes. Different softening agents were used - AE-150, AE-300, AC2.5, Reclamite and Mobilsol. It was determined that indices obtained from the gyratory compactor could be used to determine the optimum binder content of a recycled mix and that most of the rejuvenating action took place during the compaction process. A short term investigation was conducted to determine the effect of gradation on the behavior of recycled mixtures, 3 different gradations, two binder types (EA and Foamed Asphalt) and two levels of binder content (0.5% and 1.0%). Some differences in behavior were observed. These differences were primarily due to the difference in surface area.					
17. Key Words Cold recycling, creep test, softening agents, blending curves, gyratory compaction, recycling guidelines, resilient modulus			18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.		
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Final Report  
AN INVESTIGATION OF RECYCLING BITUMINOUS PAVEMENTS

by

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Joint Highway Research Project

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Conducted by

Joint Highway Research Project  
Engineering Experiment Station  
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in cooperation with the  
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and the

U.S. Department of Transportation  
Federal Highway Administration

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data represented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

Purdue University  
West Lafayette, Indiana  
March 24, 1983



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## HIGHLIGHT SUMMARY

This is the Final Report dealing with the project on the recycling of bituminous pavements. The project was quite comprehensive in its scope and was divided into several Tasks and assigned to three investigators. This final report attempts to summarize the four interim reports that were developed as a result of their findings. The reader is directed to the four interim reports when more detailed information is desired concerning test procedures and results.

A special section of this Final Report is devoted to a study that was undertaken to correct an oversight in the original project. The study involved three gradations of virgin aggregate plus salvaged material. The gradation designated as C was outside the specifications especially for material passing the #4. Two levels of binder material were used - 0.5% and 1.0%. Two types of binder material were used - an AE150 asphalt emulsion and a foamed asphalt.

Resilient modulus, Hveem R- values, Marshall stability and Marshall flow were determined. Prior to the mechanical tests, unit weights of the samples were obtained.

The highest test values were measured on specimens made from the B gradation which followed the maximum density log 45 line for the 1/2 inch top sized aggregate used. The primary differences noted were primarily due to the different surface areas of the three gradations.

The limited information obtained in this study indicates that a wider range of binder contents should be used in an expanded version of this type of study since the optimum asphalt contents would seem to fall outside those used in this study.



The report by McKinney (1) presented a set of guidelines that could assist the pavement engineer in determining if an existing asphalt pavement was a candidate for recycling. The guidelines provide a formal method for evaluating the existing pavement structure, identifying its rehabilitation needs, determining the probable cause of distress or failure, as well as identifying an appropriate recycling method. A set of construction guidelines was developed to assist the construction engineer in implementing the recycling method identified by the recycling guidelines. A section of an Indiana highway was selected to demonstrate the use of the recycling guidelines. The existing pavement structure was fully characterized and a recycling rehabilitation method, including pavement design and mix design, was selected and formulated using the procedures developed in this study.

The report by Tia (2) presented the effects of the following factors on the properties of a cold-recycled asphalt mixtures: amount and type of added binder (AE-150, AE-90, MC-3000 and AC 2.5), amount of added moisture, added virgin aggregate, the compactive effort and curing time. A laboratory procedure for preparing and testing cold recycled mixtures was developed. A water sensitivity test was used to evaluate the resistance of the recycled mixtures to water.

The report by Iida (3) presented the results of a study that dealt with the long-term behavior of recycled mixtures especially when the recycling is done cold. The long-term properties of laboratory specimens prepared with different softening agents were evaluated by means of a creep test. A design procedure was developed for cold recycled mixtures which recommends that blending curves be developed and that a creep test be used to determine mixture properties over a period of time.



The report by Tia (4) presented the effect of the following factors on the behavior of cold-recycled asphalt mixtures: two types of pavement material, three levels of oxydized condition of the old binder, two softening agents (AE-150, and foamed asphalt) and three rejuvenating agents (Reclamile, Mobilsol and DUTREX 739). The results of the study indicated that most of the rejuvenating action of the added agents on the old binder took place during the compaction process. Also, it was determined that gyratory indices could be used to determine the optimum binder content of a recycled mix. A mix design for cold recycled asphalt mixes was recommended.





## SECTION I

### EVALUATION OF DIFFERENT AGGREGATE GRADATIONS UPON THE BEHAVIOR OF RECYCLED MIXTURES

#### Acknowledgements

The authors of this report also acknowledge the important contributions of Mr. Michael Paulson in the preparation of Section I.



EVALUATION OF DIFFERENT AGGREGATE GRADATIONS  
UPON THE BEHAVIOR OF RECYCLED MIXTURES

1. INTRODUCTION.

The purpose of this report is to evaluate the effect of three different aggregate gradations upon the behavior of recycled mixtures.

This study was undertaken to correct the omission made in the project titled "Characterization of Cold-Recycled Asphalt Mixtures, Task J", authored by Drs. Mang Tia and Leonard E. Wood; conducted by the Joing Highway Research Project-Engineering Experiment Station, Purdue University, in cooperation with the Indiana Department of Highways and the US Department of Transportation Federal Highway Administration. It is presented in an Interim Report, Project No. C-36-21D, File No. 2-8-4, West Lafayette, February 2, 1982 [1]\*.

The separate study presented here called for three specimens per cell. The three gradations proposed in the amended work plan -mid-range, upper level of the grading band, and one which follows the maximum density log 45 line for the top size of the aggregate used ( $\frac{1}{2}$  in) were obtained by blending varying amounts of crushed stone virgin aggregate and salvaged pavement. Two levels of binder material were used - 0.5% and 1.0%. Two types of binder material were added to the aggregate - asphalt emulsion (AE-150), and foamed asphalt (AC-20). One compactive effort - gyratory, 20 revolutions at 200 psi, was used in preparing the test samples.

---

\*Note: Numbers in brackets refer to entries in the Bibliography.



Resilient modulus, Hveem R-values, Marshall stability, and Marshall flow, were determined on specimens subjected to a standard curing period of one day (in the mold), at room temperature (72°F). Prior to the mechanical tests, unit weights of the samples were obtained. A description of the materials used and a summary of the results obtained from this amended work study, follows next.

## 2. BINDER AND AGGREGATE MATERIALS.

Two types of binder material were used in this investigation. An asphalt emulsion AE-150 (70% asphalt residue + 30% water), and foamed asphalt AC-20. Each binder was added to the aggregate material at two levels: 0.5% and 1.0% of asphalt residue content.

The virgin aggregate (crushed stone) added to the recycled material, produced a mid range gradation (gradation A); another in the upper level of the grading band of Indiana 1978 Specification Limits, Gradation No. 11-III, (gradation C), and finally, the maximum density log 45 line for the top size of the aggregate used, namely,  $\frac{1}{2}$  inch (gradation B). These different gradations are depicted in Figure 1, together with the Standard Specification No. 11-III limits. The percentages of aggregate material passing the different standard sieve sizes, are listed in Table 1.



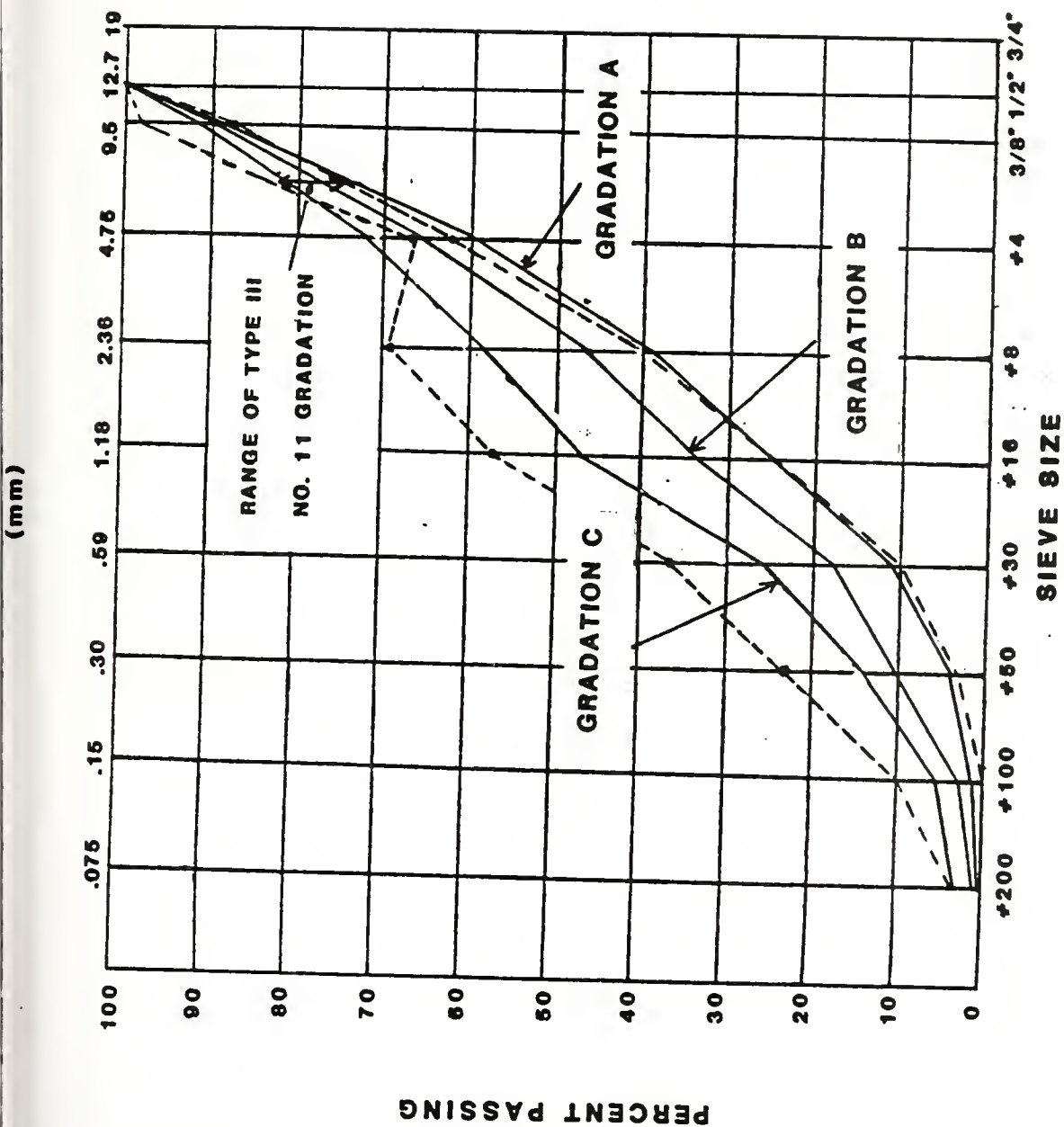


FIGURE 1 AGGREGATE GRADATION





TABLE 1. GRADATION OF AGGREGATE MATERIAL  
(RECYCLED + VIRGIN MATERIAL)

<u>Sieve Size</u>	<u>AGGREGATE (% Passing)</u>		
	<u>A</u>	<u>B</u>	<u>C</u>
1/2"	100.0	100.0	100.0
3/8"	87.9	88.8	91.8
# 4	57.9	66.2	72.5
8	38.2	46.4	57.6
16	24.8	34.0	46.8
30	10.6	17.7	25.7
50	4.4	10.4	14.0
100	1.5	3.2	5.3
200	0.0	1.0	4.4

### 3. SPECIMEN PREPARATION AND TEST PROCEDURES

The test specimens were mechanically mixed for two minutes in batches of three samples, followed by  $\frac{1}{2}$  minute hand mixing. They were compacted in the gyratory testing machine with 20 revolutions at 200 psi and left aside, in the mold, for 24 hours curing at room temperature. After the samples were extruded from the mold, the following test procedures were performed in the respective sequence: unit weight, resilient modulus, Hveem R-value, and Marshall test. The reader can consult the reference cited in the "Introduction" section of this report (reference No. 1), where these test procedures are described in greater detail.



#### 4. PRESENTATION OF RESULTS

Several terms can be used to provide a single number to describe the shape and range of the grain size distribution curve, or gradation of a sample of aggregate material. Such terms can be either gradation coefficients or gradation indices. In this study, the different aggregate gradations used (virgin aggregate plus recycled material), (see Figure 1), were characterized by the Aggregate Gradation Modulus ( $\bar{A}$ ), their Fineness Modulus (FM), the percentage of Material Passing the No. 4 Sieve, and their Surface Area.

The test parameters obtained in this study, namely: resilient modulus, Hveem R-values, Marshall stability values, and unit weight results, were plotted in the graphs described next. The values plotted in these figures are the average of test result values obtained from three specimens tested under similar conditions.

a) Aggregate Gradation Modulus ( $\bar{A}$ ). - The review of the literature, revealed that the Aggregate Gradation Modulus ( $\bar{A}$ ), was an appropriate parameter to be used in the final analysis of the significance of the test results [2, 3, 4, 5]. The relative coarseness of an aggregate gradation can be expressed by the Aggregate Gradation Modulus or Hudson  $\bar{A}$  [3], which is a single number reflecting the amount of material passing the ten standard sieves from  $1\frac{1}{2}$  in. through the No. 200 sieve. This value is related to the surface area of the aggregate and is sufficiently sensitive to reflect changing requirements for mix proportions or asphalt content as the aggregate grading varies.



The number  $\bar{A}$  is most easily computed using standard sieves. The percentages passing sieves  $1\frac{1}{2}$  in.,  $\frac{3}{4}$  in.,  $\frac{3}{8}$  in., No. 4, 8, 16, 30, 50, 100, and No. 200, should be added as shown in Table 2, and then divided by 100. This table presents the calculated  $\bar{A}$  values for the three different gradations used in this study, as well as for the maximum gradation curve log 0.50 line of a  $\frac{1}{2}$  in. top size aggregate, shown for comparison purposes. The results thus obtained ranged from a low of 4.25 to a high of 5.18.

TABLE 2. AGGREGATE GRADATION MODULUS ( $\bar{A}$ ), FOR  
GRADATIONS A, B, C, AND  $\frac{1}{2}$  IN. MAX. DENSITY.

<u>S. S.</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u><math>\frac{1}{2}</math> in. Max. Dens.</u>
1 $\frac{1}{2}$ in	100.0	100.0	100.0	100.0
$\frac{3}{4}$	100.0	100.0	100.0	100.0
$\frac{3}{8}$	87.9	88.8	91.8	86.6
No. 4	57.9	66.2	72.5	61.2
8	38.2	46.4	57.6	51.0
16	24.8	34.0	46.8	43.0
30	10.6	17.7	25.7	30.0
50	4.4	10.4	14.0	15.4
100	1.5	3.2	5.3	10.9
200	0.0	1.0	4.4	7.7
<hr/> All:	<hr/> 425.3	<hr/> 467.7	<hr/> 518.1	<hr/> 505.8
Aggregate Gradation Modulus ( $\bar{A}$ ):	4.25	4.68	5.18	5.06



An investigation of theoretical concepts, confirmed by limited experimental investigation, [4, 5], indicates that  $\bar{A}$  is a fundamental constant, related to the relative surface area effects of the aggregate gradation in any mixture of particle sizes. For example, with asphaltic concrete aggregates in the usual range of  $\bar{A}$  from 4.00 to 6.00 (as in the case of this study), a change of 0.50 in the value of  $\bar{A}$ , according to Hudson, would change the asphalt demand by about 1.0% by volume, which is enough to affect the performance of the mix.

The effects of the relative coarseness of the aggregate as obtained from this laboratory study, are graphically presented in Figures 2 through 4. Figure 2 depicts the Average Resilient Modulus values (in psi.) obtained for aggregates A, B, and C (see Table 1), versus their corresponding Aggregate Gradation Modulus ( $\bar{A}$ ) presented in Table 2.

Figure 3 shows the Average Hveem R-value versus the Aggregate Gradation Modulus ( $\bar{A}$ ), of all three aggregates used. Figure 4 presents Marshall Stability values (in lbs.), versus  $\bar{A}$ ; and Figure 5 depicts Unit Weight values (in pcf.), for all the specimens tested, against the gradation coefficient  $\bar{A}$ .

b) Aggregate Fineness Modulus (FM). - The Fineness Modulus, originated by Abrams, is a parameter more useful when dealing with aggregates for portland cement concrete. The FM was intentionally designed to exclude the influence of the percentage of material passing No. 100 sieve [3], (see Table 1). This, therefore, makes the FM less suitable than for example  $\bar{A}$ , for use in dealing with aggregates for





FIGURE 2.-AVG. RESILIENT MODULUS VS. AGG.G.MOD.

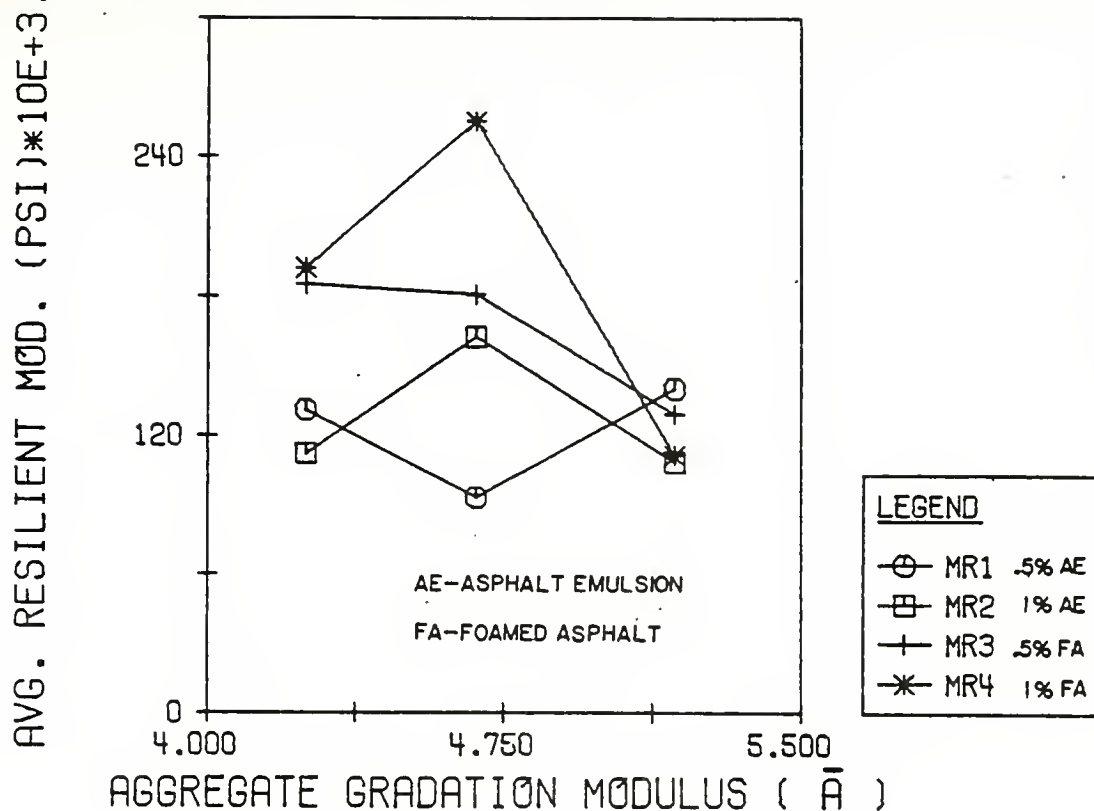


FIGURE 3.-AVG. HVEEM R-VALUE VS. AGG.GRAD.MOD.

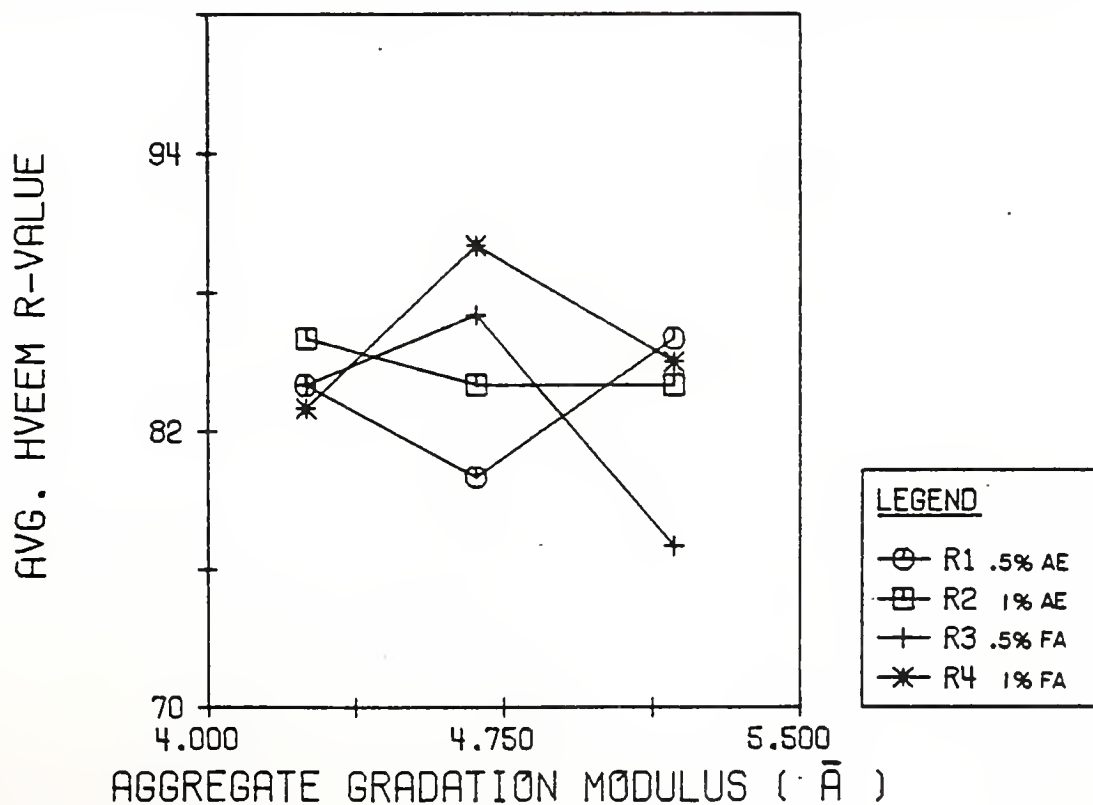




FIGURE 4.-AVG. MARSHALL STABILITY VS. AGG.G.MOD.

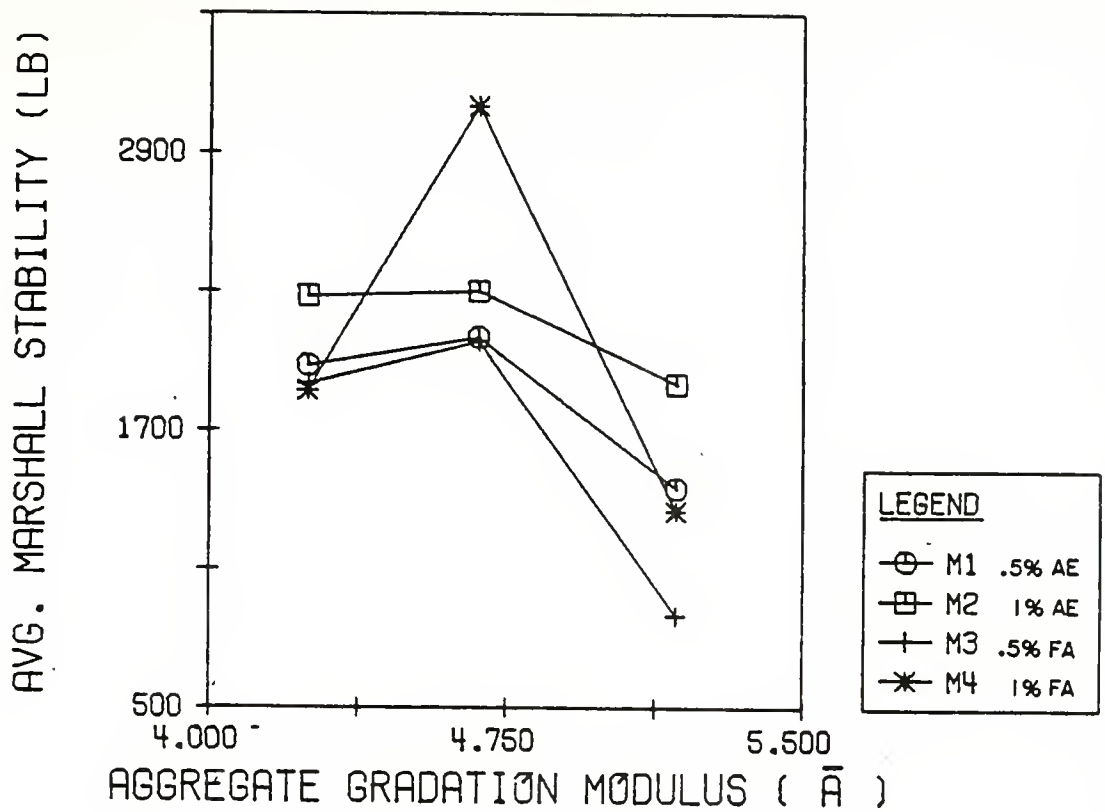
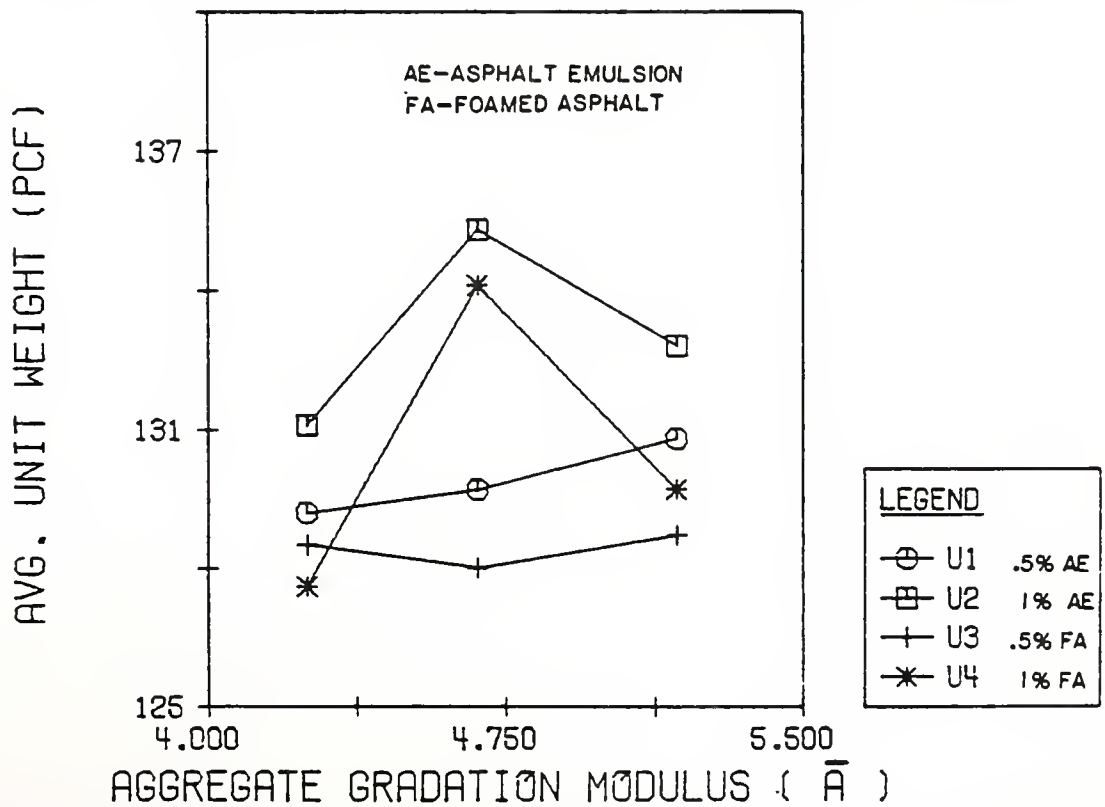


FIGURE 5.-AVG. UNIT WEIGHT VS. AGG.GRAD.MOD.





bituminous concrete or when other aggregate mixtures contain a significant quantity of minus No. 100 material. The Fineness Modulus values obtained for gradations A, B, C, and  $\frac{1}{2}$  in. maximum density, were calculated by adding the percents passing, presented in Table 1 of this report, from  $\frac{1}{2}$  in. sieve size, through No. 50, and dividing them by 100. Table 3 is a list of the FM values thus obtained.

TABLE 3. AGGREGATE FINENESS MODULUS FOR  
GRADATIONS A, B, C, AND  $\frac{1}{2}$  IN. MAX. DENSITY

<u>S. S.</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u><math>\frac{1}{2}</math> in. Max. Density</u>
$\frac{1}{2}$ in.	100.	100.	100.	100.
:	:	:	:	:
:	:	:	:	:
50	4.4	10.4	14.0	15.4

Aggregate  
Fineness

Modulus (FM):            3.24      3.64      4.08            3.87

Figures 6, 7, 8, and 9, show the same sequence of test results described before, (resilient modulus, Hveem R-value, Marshall stability,



FIGURE 6.-AVG. RESILIENT MODULUS VS. AGG.FM

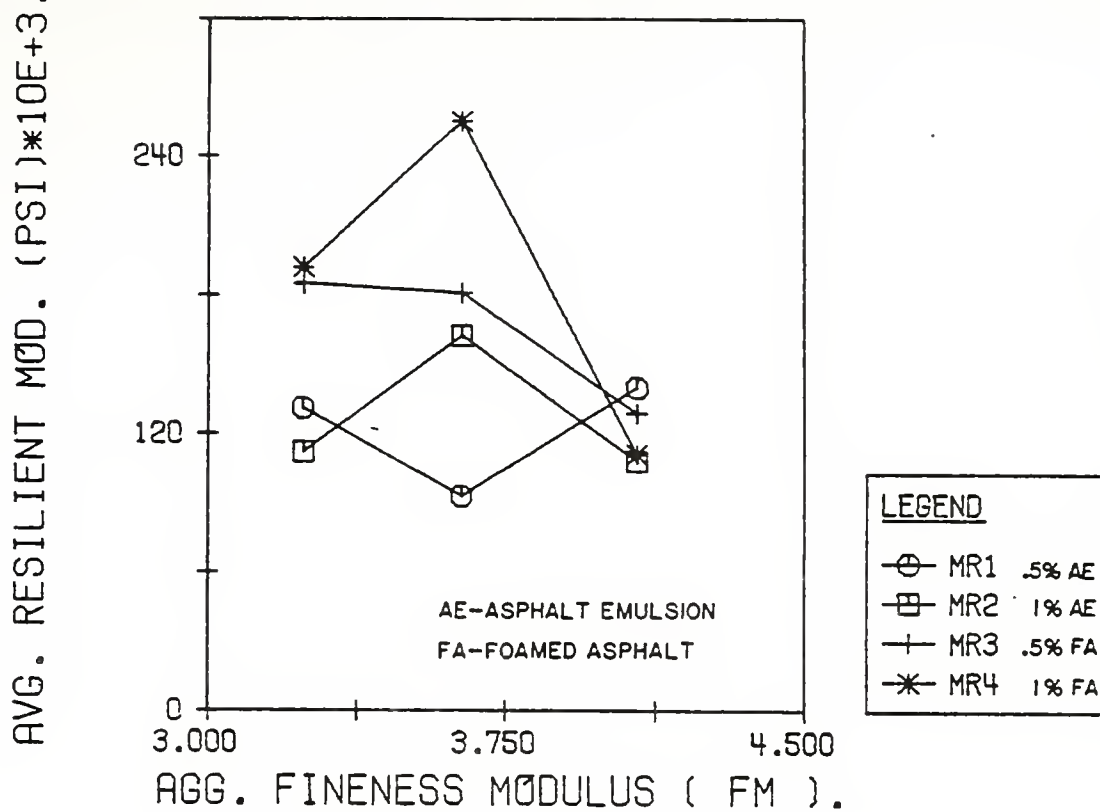


FIGURE 7.-AVG. HVEEM R-VALUE VS. AGG. FM

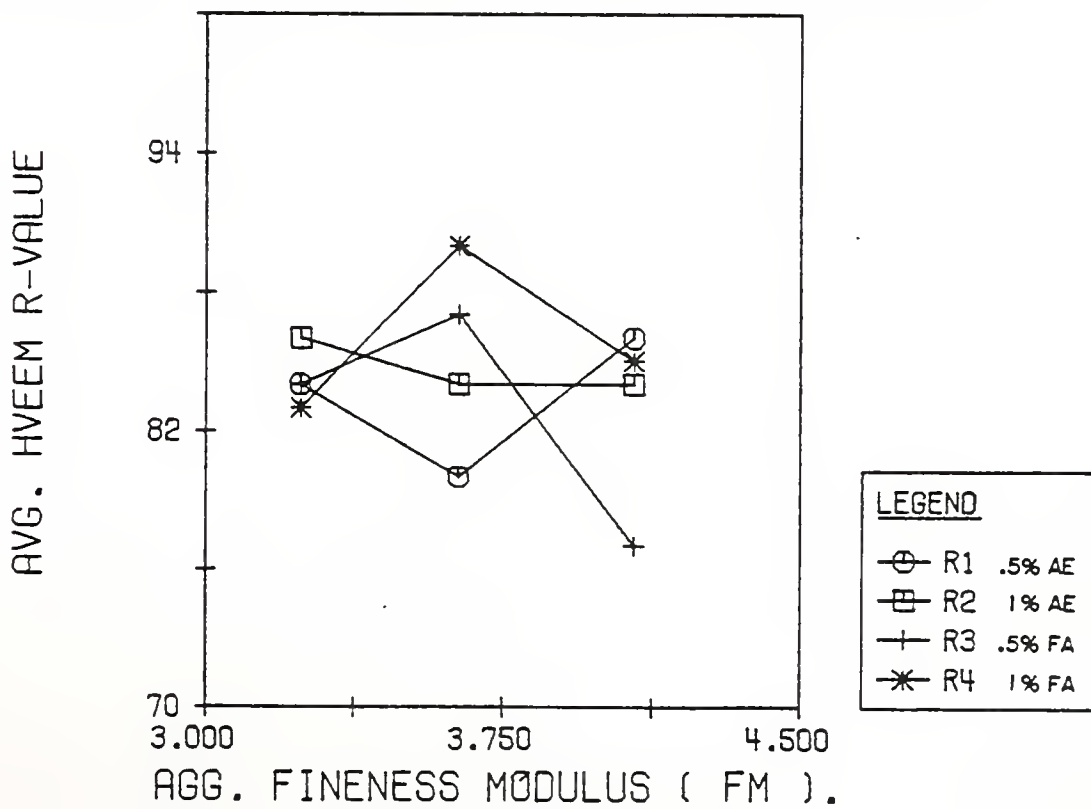






FIGURE 8.-AVG. MARSHALL STABILITY VS. AGG.FM

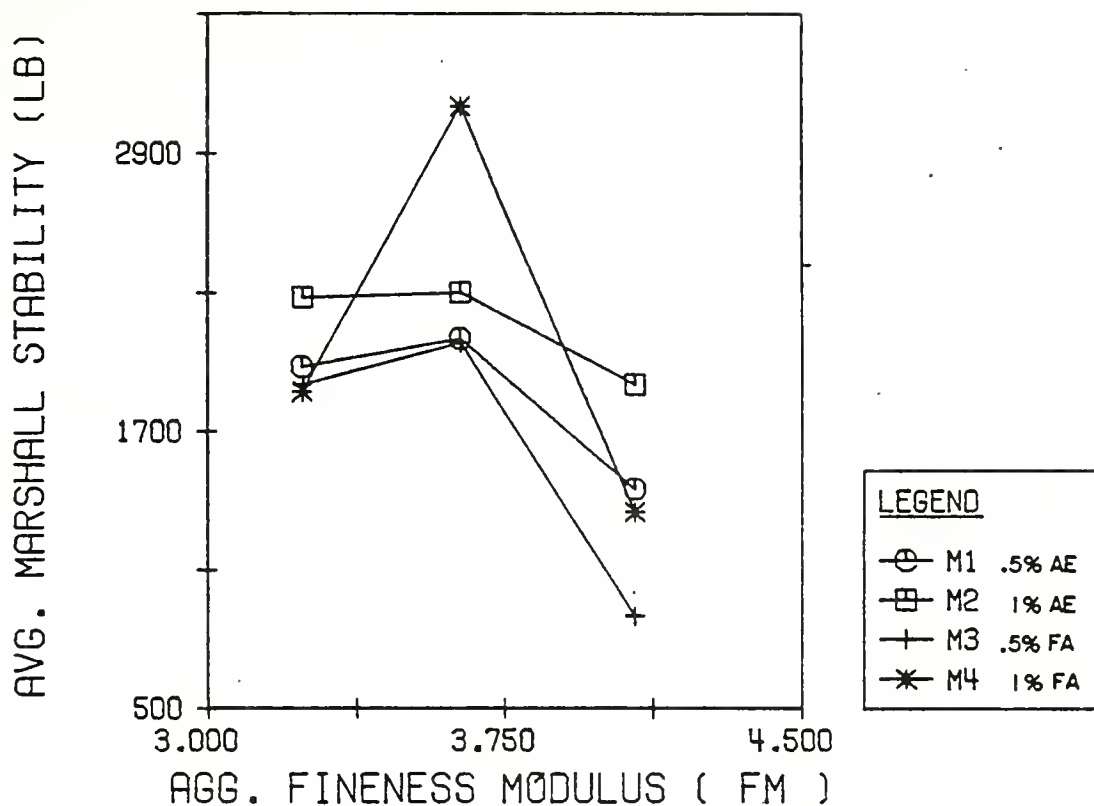
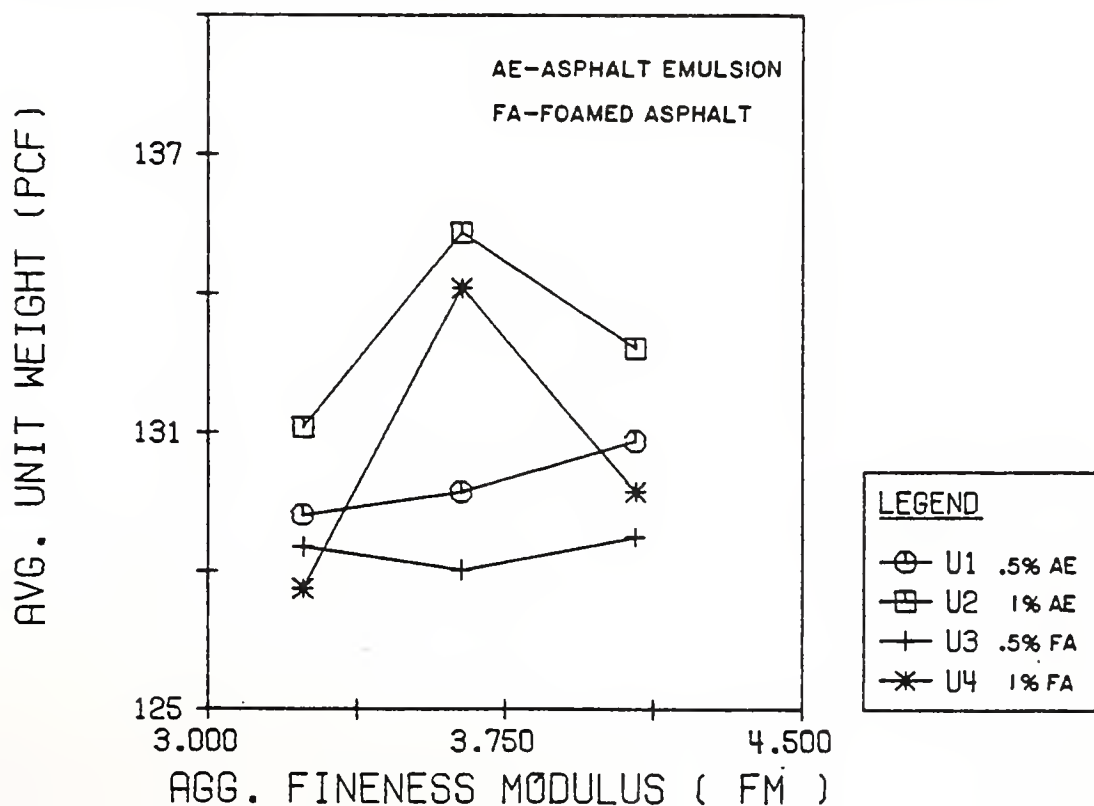


FIGURE 9.-AVG. UNIT WEIGHT VS. AGG. FM





and unit weight), plotted against the Fineness Modulus values (FM) obtained for each gradation used.

c) Percentage of Material Passing No. 4 Sieve. - Resilient modulus, Hveem R-value, Marshall stability, and unit weight test results, were plotted in Figures 10, 11, 12, and 13, against the Percentage of Material Passing the No. 4 sieve, for the different gradations examined. This gradation parameter was used to characterize the various aggregates in terms of their relative amounts of fines. The increase in surface area of the aggregate (larger amounts of fines), can imply high requirements of binder content in a bituminous mix as compared with aggregates that are relatively more "clean". Table 4 shows the amounts of material passing and retained in the standard sieve size No. 4.

TABLE 4. PERCENTAGE OF MATERIAL PASSING THE NO. 4  
SIEVE, FOR GRADATIONS A, B, C, AND  $\frac{1}{2}$  IN. MAX. DENS.

<u>S. S.</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u><math>\frac{1}{2}</math> in. Max. Density</u>
> No. 4	42.1	33.8	27.5	38.8
< No. 4	57.9	66.2	72.5	61.2
<hr/>	<hr/>	<hr/>	<hr/>	<hr/>
All:	100.0	100.0	100.0	100.0



FIGURE 10.-AVG. RESILIENT MOD.VS. PERC.&lt;# 4.

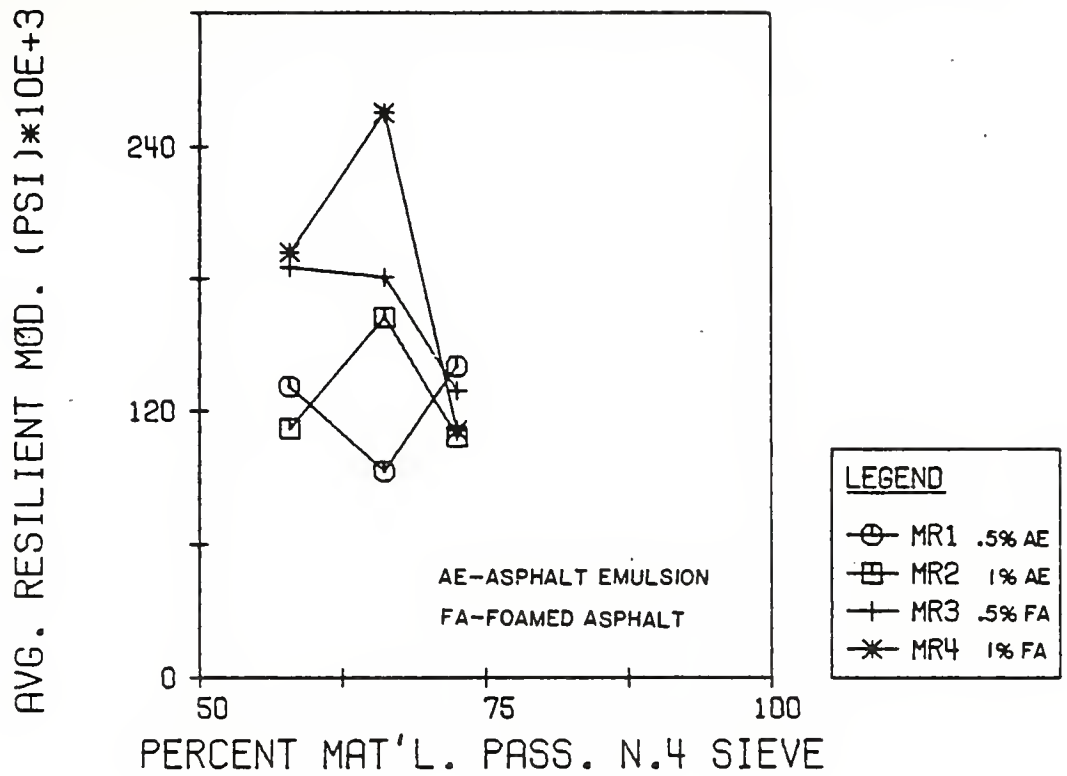


FIGURE 11.-AVG. HVEEM R-VALUE VS. PERC.&lt;#4.

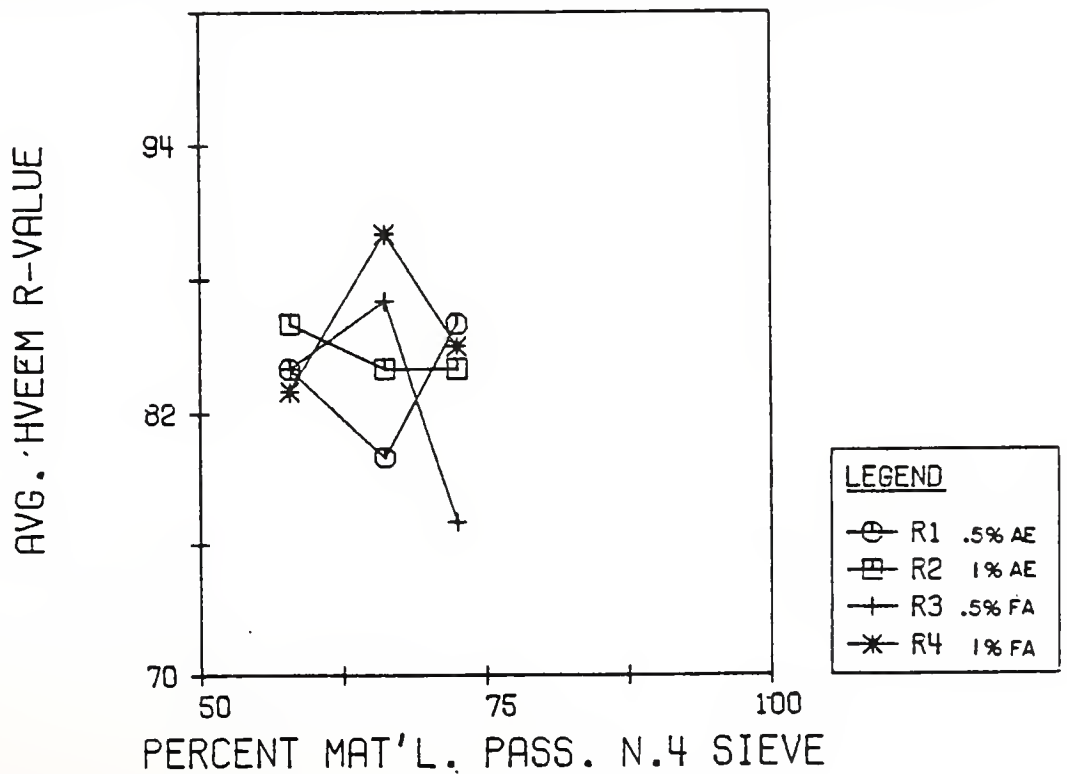




FIGURE 12.-AVG. MARSHALL STAB. VS. PERC.&lt; #4.

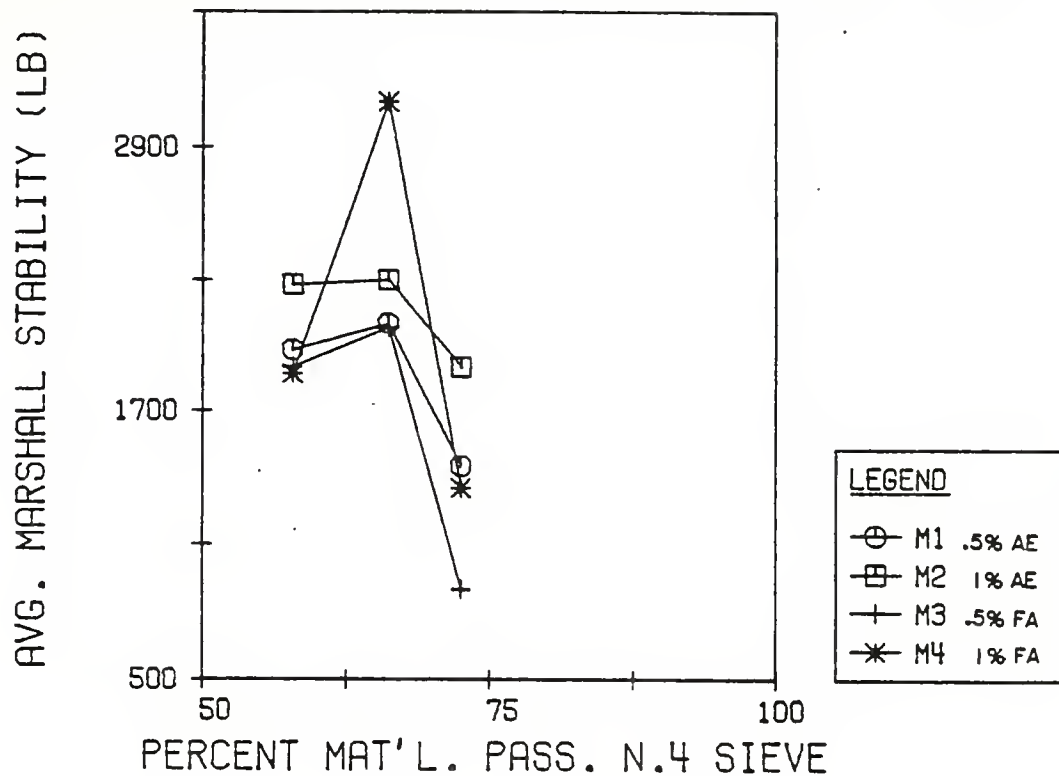
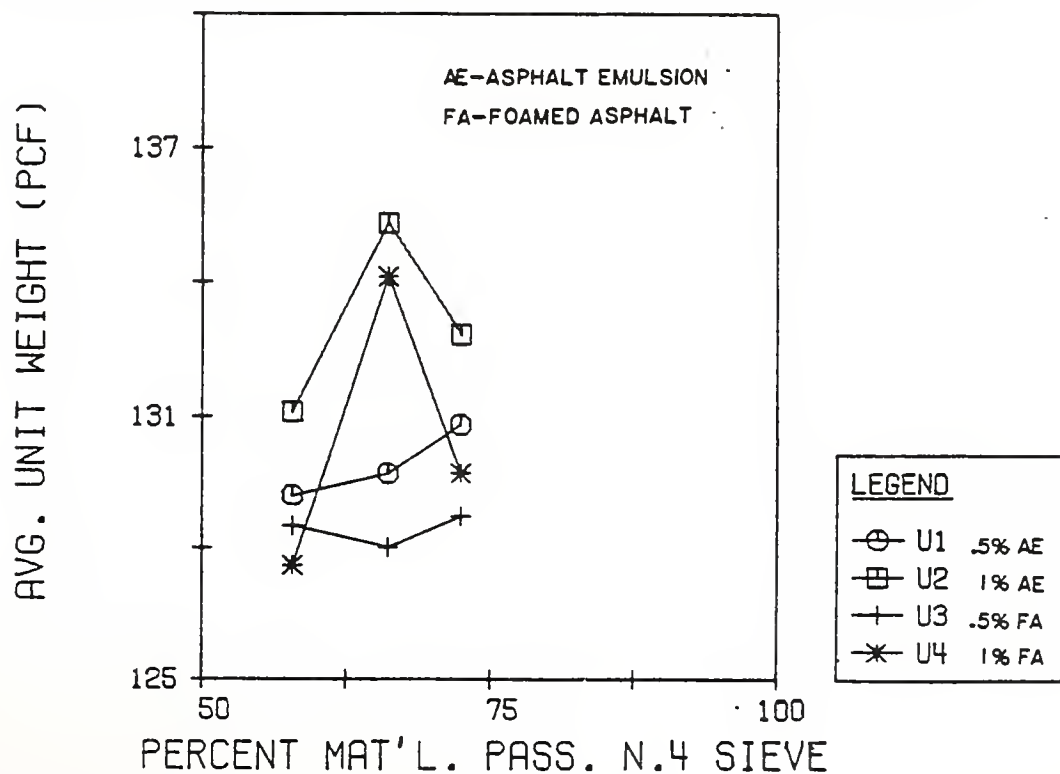


FIGURE 13.-AVG. UNIT WGHT. VS. PERC.&lt; #4.







d) Surface Area. - Variations in gradation have effects such as the change in surface area of the aggregate. This in turn, will affect the optimum asphalt content of bituminous mixtures as well as water requirements for mixing purposes. Another gradation parameter used to characterize different gradations is the surface area of the aggregate. The calculation of this parameter consists of multiplying the total percent passing each sieve size by a "surface area" factor, as set forth in Table 5. Then, the products thus obtained, are added, and the total will represent the equivalent surface area of the sample in terms of square feet per pound [6].

TABLE 5. SURFACE AREA FOR GRADATIONS

A, B, C, AND  $\frac{1}{2}$  IN. MAX. DENSITY

S. S.	SA Factor	x Corresponding % Passing	A	B	C	$\frac{1}{2}$ in. Max. D.
1/2 in						
3/8	2	.....	2.0	2.0	2.0	2.0
No. 4	2	.....	1.2	1.3	1.5	1.2
8	4	.....	1.5	1.9	2.3	2.0
16	8	.....	2.0	2.7	3.7	3.4
30	14	.....	1.5	2.5	3.6	4.2
50	30	.....	1.3	3.1	4.2	4.6
100	60	.....	0.9	1.9	3.2	6.6
200	160	.....	0.	1.6	7.1	12.3
SURFACE AREA (FT <sup>2</sup> /lb):			10.4	17.0	27.6	36.3



FIGURE 14.-AVG. RESILIENT MOD.VS. SURF. A.

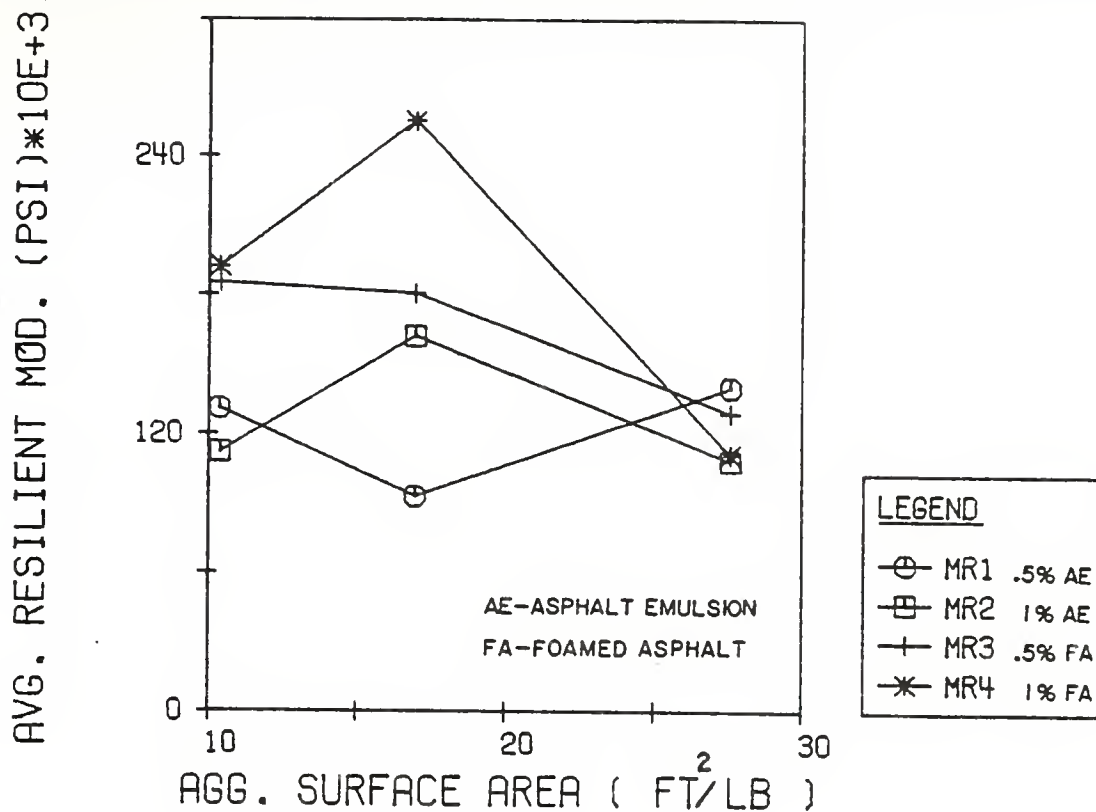


FIGURE 15.-AVG. HVEEM R-VALUE VS. SURF. A.

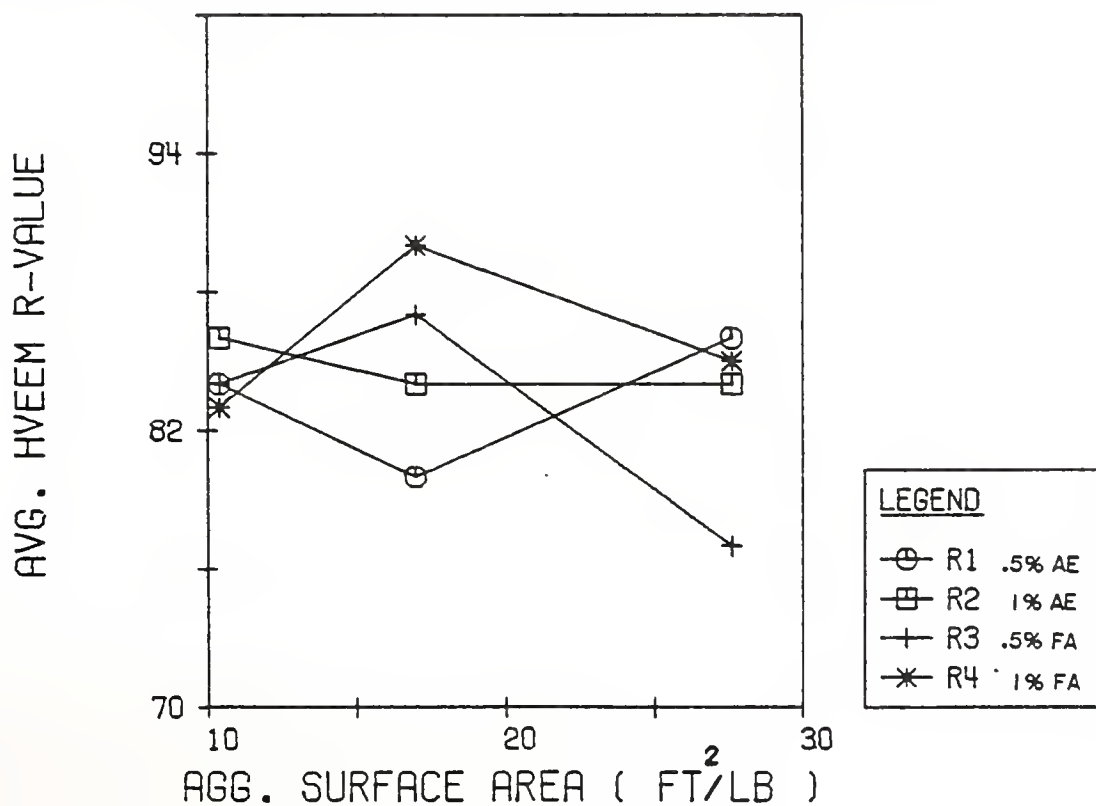




FIGURE 16.-AVG. MARSHALL STAB. VS. SURF.A.

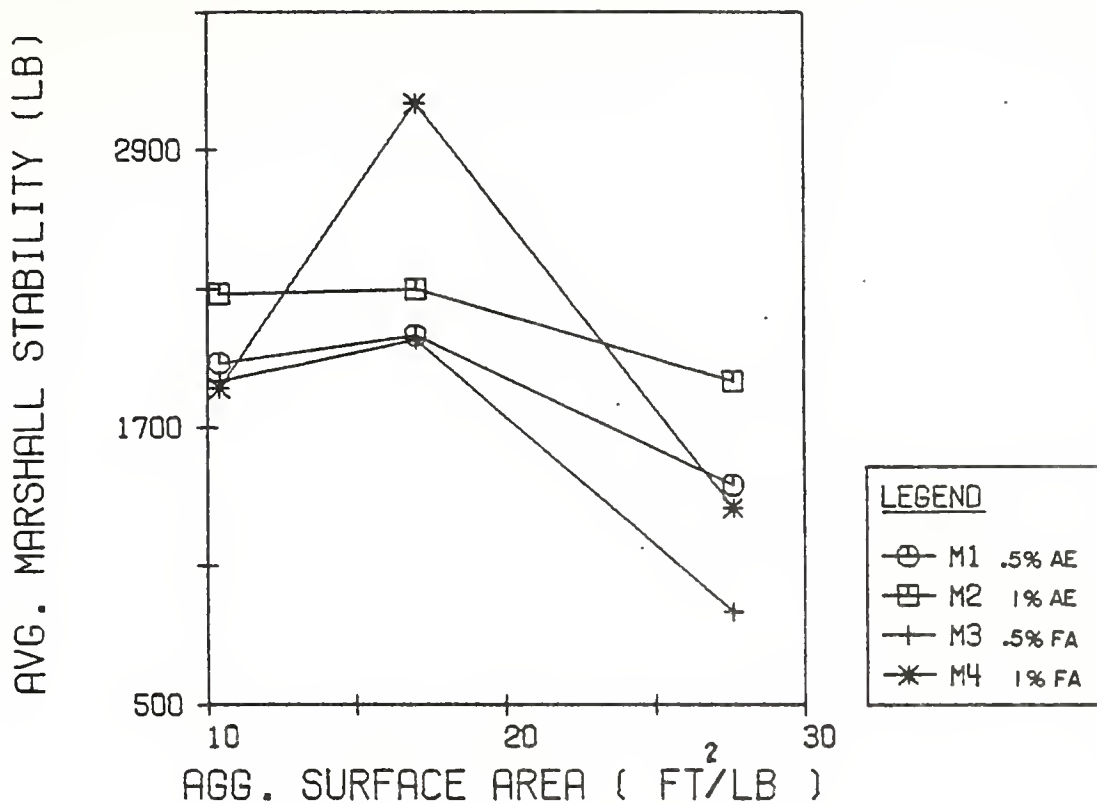
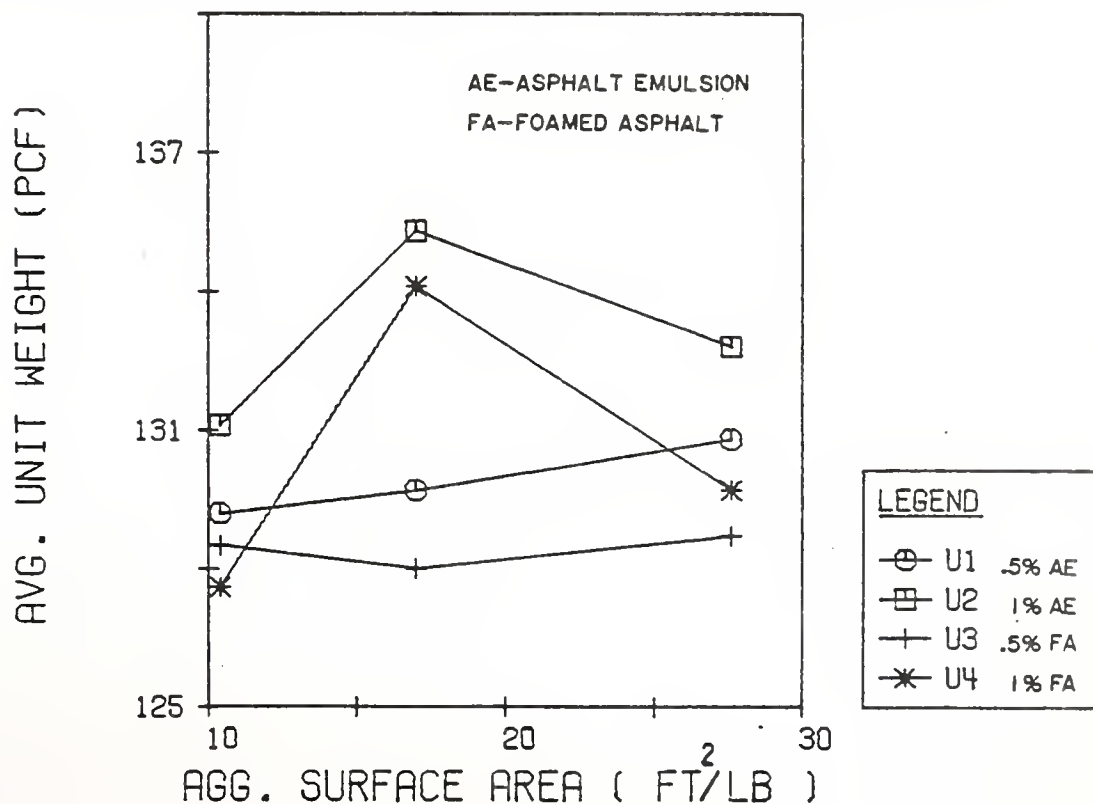


FIGURE 17.-AVG. UNIT WGHT. VS. SURF. A.





## 5. DISCUSSION OF RESULTS

The results presented in the foregoing section of this report as well as the discussion of them, are limited to the range of variables used in this study; namely: crushed stone as the virgin aggregate material, gradation differences such as for gradations A, B, and C, and asphalt residues of 0.5 and 1.0% for an asphalt emulsion AE-150 and an AC-20 foamed asphalt. The specimen preparation and testing is limited to the methods described in Section 3 of this report.

Since the various gradation parameters used in expressing the effects of the different gradations used in this study, depicted almost the same trends, a more thorough discussion will be made of results based on the Hudson  $\bar{A}$  parameter. The different trends observed appear to be due to the changes in total surface area of the gradations used, which in turn affects the required optimum binder content. This affects some properties of the final mix such as density and strength.

The resilient modulus values obtained for gradation C ( $\bar{A} = 5.18$ ) using various types and amounts of binder, as shown in Figure 2, were almost the same. A wider range of resilient modulus values can be observed for gradations B and A, ( $\bar{A} = 4.68$  and  $4.25$  respectively). This tends to indicate that the effects of surface area are more pronounced in aggregates with lower Hudson  $\bar{A}$  values than for those with larger ones, in terms of resilient characteristics of the mix.

In general, resilient modulus values obtained using asphalt emulsion were lower as compared with those obtained using foamed asphalt. All figures presenting resilient modulus data suggest that at  $\bar{A} = 4.68$  (gradation B),





laboratory investigation of the behavior of col-recycled asphalt pavement mixtures that was conducted by Iida (3) and Tia (2,4).

#### Effect of Added Agent

In an old pavement material, an aggregate piece is surrounded by a hardened layer of binder. During the recycling process, a thin film of virgin binder or softening agent is established. This thin film of virgin binder or softening agent will have rejuvenating effect on the old binder material. The rejuvenating action that takes place is dependent on time, temperature and additional traffic compaction. If too much of the old binder material is "activated" through the rejuvenating action, the mix will have too rich an asphalt content, and problems such as instability and bleeding will occur. (Bleeding is the upward movement of asphalt in a pavement, creating a film of asphalt on the surface). If not enough virgin asphalt or softening agent is added, the mix will be too lean in asphalt content, and it will not have the desirable durability and flexibility.

A laboratory study conducted by Tia (2,4) investigated the effects of different factors on the properties of cold-recycled asphalt mixtures. The factors included the amount and type of added binder, the amount of added moisture, added virgin aggregate, the compactive effort and curing time. A brief summary of this study are reported in the following sections. The reader is directed to interim reports (2,4) when greater detail is required.

The added agents used in the laboratory study include three asphalt emulsions (AE-90, AE-250 & AE-300), three rejuvenating agents



higher values were obtained for mixtures made with 1% of binder content as compared with those made at 0.5% binder (see Figures 2, 6, 10, and 14.) At  $\bar{A} = 5.18$  the trend is reversed, with lower binder contents giving slightly higher resilient modulus values.

Hveem Resistance values presented in Figure 3, against Hudson  $\bar{A}$ , show essentially the same trends described before, except for the low values observed for mixtures prepared at 0.5% foamed asphalt, at  $\bar{A} = 5.18$ . This can also be observed in Figures 7, 11, and 15.

Figure 4 depicts average Marshall stability values that essentially remained unchanged for aggregate gradation modulus values lower than 5.0. An exception is noticed for mixtures prepared with 1% foamed asphalt, where at  $\bar{A} = 4.68$ , a high stability value is recorded. Marshall stability of the mixtures prepared with gradation C ( $\bar{A} = 5.18$ ), show in all cases (see Figure 8, 12, and 16), a lowering trend, for all types and amounts of binder.

High density values as shown in Figures 5, 9, 13, and 17, obtained for 1% binder content using gradation B, appear to explain the high values of resilience and stability obtained for these mixtures. The general trend observed for all mixes prepared at 0.5% binder content, is of increasing unit weight with the increment of aggregate gradation modulus ( $\bar{A}$ ). The values obtained with 1% binder content, show a peak, for mixtures prepared with gradation B. This suggest that better lubrication is obtained using more binder which in turn enables better aggregate orientation that finally brings a denser mix. However, the results obtained for mixtures made with gradation C, suggest that more surface area ( $\bar{A} = 5.18$ ) possibly requires binder contents in excess than 1% in order to reach higher measured values.



## 6. RECOMMENDATIONS FOR FURTHER RESEARCH

The limited information obtained in this study indicates the need for expanding future investigations in order to make any broad ranging statements concerning the effects of aggregate gradation upon the behavior of cold recycled mixtures. This can be obtained by including a wider range of aggregate gradations and binder contents to be used in the study.

The changes in surface area of the aggregate (different gradations), appears to affect the required binder contents, possibly in a wider range than the ones used in this investigation (0.5 to 1%). With mixtures prepared at optimum binder contents, the particular effect produced by differences in gradation can be evaluated, independently of any other factor affecting the ultimate characteristics of the mix.



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## SECTION II

Summary of HPR-1(18) Part II

AN INVESTIGATION OF RECYCLING  
BITUMINOUS PAVEMENTS



## INTRODUCTION

One of the major problems confronting the transportation agencies in the United States today is the maintenance and rehabilitation of the existing highway system with the decreased level of funding. In recent years, the overall condition of the highway systems have been declining, as a result of the fact that the actual expenditure on pavement rehabilitation has not been able to keep up with the cost needed to preserve the conditions of the existing roadways. One of the ways to ease this crisis is through the more effective and more efficient utilization of the available resources. Asphalt pavement recycling is a rehabilitation method which has been shown to be economical as well as effective, if done properly. Besides the substantial savings in cost, the benefits of pavement recycling include conservation of asphalt and aggregate resources, reduction in fuel consumption, preservation of pavement geometries and reduction in environmental pollution.

Asphalt pavement recycling is the technique of putting the existing pavement material back into use. The fundamental concept of asphalt pavement recycling lies in upgrading the deteriorated aggregates by the addition of virgin aggregates and softening the hardened old asphaltic binders by the addition of rejuvenating agents. Basically, it involves (1) removing the old pavement material from the road, (2) mixing it when necessary with additional virgin aggregate, a virgin binder or a softening agent, and (3) repaving it. This process can be done either hot or cold (i.e. with or without the application of heat). The advantages of the cold process as compared to the hot process are the less fuel consumption, the simpler construction equipment, and thus the lower



construction cost. However, the finished product of the cold recycling process is generally not as stable as that produced by the hot process. Thus, at present, cold-mix recycling is used only on low volume roads. More work still remains to be done to improve the quality of the cold recycled mixture, so that it could be used on interstate highways and other high volume roads. Such a breakthrough would mean eventual replacement of hot recycling by cold recycling and a drastic reduction of pavement rehabilitation cost.

The purpose of this study was to fully investigate asphalt pavement recycling through literature review, laboratory study and analysis of actual recycling projects. The types of equipment used and the construction methods for the various recycling methods were reviewed and evaluated. The behavior of cold-recycled asphalt paving mixtures were investigated in the laboratory study. Various recycling jobs were analyzed to determine rates of production, unit costs, unit rates of energy consumption and specific problems encountered during recycling operations.

The main objectives of the study are as follows:

1. To fully understand the behavior of cold-recycled asphalt mixtures under the effects of the kind and amount of added agent, the added virgin aggregate, the added moisture, the compactive effort, the testing temperature and the curing time.
2. To develop guidelines for the design of cold-recycled asphalt mixtures.



3. To develop recycling guidelines for evaluating an existing pavement structure, identifying its rehabilitation needs, determining the probable cause of distress or failure and identifying an appropriate recycling method.
4. To develop construction guidelines for implementing the recycling method identified by the recycling guidelines.

The major findings in this study are summarized in this report.

## SURVEY OF BITUMINOUS PAVEMENT RECYCLING

A detailed study on Bituminous Pavement Recycling was conducted by McKinney (1). A review of his study are presented in the following sections.

### Surface Recycling

Surface recycling is one of the most widely used forms of asphalt pavement recycling. This method is primarily used for correcting or rehabilitating the surface layer of asphalt pavements. Surface recycling is particularly well suited for treating or correcting surface deficiencies, as well as pavement geometry problems. A majority of surface related defects can be attributed to the oxidation of the pavement binder that occurs in the upper layer of the pavement surface. Surface recycling either removes this layer of aged material or rejuvenates the material, so that near original binder properties can be restored to the pavement surface. Successive new material overlays can cause problems





with vertical clearances, roadway cross-slopes, curb reveal, utility covers and drainage structures. Removing excess surface material, with surface recycling techniques, prior to a new material overlay can eliminate these problems.

Surface recycling can be classified into two major groups: hot surface recycling and cold surface recycling. Hot surface recycling utilizes thermal energy to heat the pavement surface material to facilitate the removal process. Several different machines can be used to accomplish this operation: heater-planers, heater-scarifiers and hot millers. The major problem associated with the use of hot surface recycling techniques is the development of the proper level of thermal energy. Excessive temperature can damage pavement materials, as well as generate excessive atmospheric pollutants. Inadequate temperature can seriously retard the pavement removal process or impede the surface recycling operation.

Cold surface recycling, rather than depending on thermal energy to aid in the pavement removal process, utilizes mechanical energy to plane or mill the pavement surface. The most prevalent type of cold surface recycling equipment is a cold milling machine which utilizes a rotating drum equipped with cutting teeth to remove the pavement surface material. Temperature related degradation of the asphalt binder and associated hydrocarbon emissions are eliminated. In general, cold millers are capable of removing more material per pass, with greater cutting accuracy, while consuming less energy per unit of material removed than hot surface recycling equipment.



### Central Plant Recycling

Central plant recycling usually involves removing the existing asphalt-bound pavement material, full depth, and transporting the salvaged material to a central plant where additional new materials may be added to the salvaged materials during a hot mixing operation. The recycled material is then put back on the roadbed with conventional paving equipment. A significant improvement in the structural capacity of the existing pavement can be achieved during this recycling operation. The base/ subbase can be reconstructed after the asphalt pavement materials are removed. The salvaged asphalt materials can be rejuvenated and upgraded during central plant mixing operations.

The salvaged material must be crushed and sized prior to recycling in the central plant. Usually, the salvaged asphaltic pavement material is crushed at the central plant site using conventional aggregate crushing equipment, although the material may be crushed in-place, on the roadbed, using mobile equipment.

Central plant recycling can be classified into two major groups: drum mixer recycling and batch plant recycling. The major problem associated with the use of central plant equipment for recycling asphaltic materials is the hydrocarbon emissions that are generated when the salvaged binder is ignited by the dryer flame. Drum mixer recycling utilizes a dual feed process to control hydrocarbon emissions. Uncoated aggregate is used to protect the salvaged asphaltic material from the high temperature of the drum mixer's burner. The uncoated aggregate also acts as a heat transfer medium that raises the temperature of the



salvaged pavement materials. Batch plant recycling also utilizes a dual feed process to eliminate hydrocarbon emissions. Uncoated aggregate is superheated in a conventional dryer, while the salvaged pavement material is introduced directly into the batch plant tower, bypassing the dryer. The salvaged pavement material is heated by the super heated, uncoated aggregate in the batch plant weigh hopper and pugmill, totally eliminating the generation of any hydrocarbon emissions. Modification components or add-on recycling kits are available for both types of central plants so that conventional equipment can be used for central plant recycling.

#### In-Place Recycling

In-Place recycling is the third major form of asphalt pavement recycling. A variety of equipment and construction techniques can be used to recycled asphaltic pavement materials in-place. Normally, the product produced by this recycling method is a cold mixed in-place stabilized base. Usually, a new material overlay or an asphalt surface treatment is applied to protect the recycled layer from traffic action, to waterproof the recycled materials and to add increased structural strength to the recycled pavement.

In-place recycling is normally accomplished using conventional road building equipment. Costly transportation operations are eliminated since the asphaltic material is recycled in-place on the roadbed. In-place recycling consumes less energy per unit of material processed than the other two major forms of recycling. The major disadvantage associated with some in-place recycling operations is the inability to control



the quality of the product that is produced. Due to the fact that such a wide variety of construction equipment and techniques are used to recycle the materials in-place, the variability associated with the final product is much greater.

The primary operations required for recycling an asphalt pavement in-place are: removal of the existing pavement; crushing and pulverization of the salvaged pavement materials; mixing of the salvaged material with additional materials (as needed); and laydown and compaction of the recycled product.

Many different types of equipment, ranging from the simple to the relatively complex, can be used to accomplish these operations. The type of new binder incorporated in the recycled mixture will control the type of mixing, laydown and compaction equipment that can be used. The quantity and quality of the existing pavement will dictate, in large part, the proper choice of equipment for removal and crushing operations. The type of equipment chosen, in turn, controls the in-place recycling rate of production, as well as greatly influencing the unit cost associated with recycling operations.

### Recycling Guidelines

As a result of this study, a set of recycling guidelines was developed and presented in Chapter 2 of the interim report "An Investigation of Recycling Bituminous Pavements" by James L. McKinney (1). This section summarizes the main points of the recycling guidelines.

The recycling guidelines establish a formal evaluation and investi-





gation procedure that can be used to determine whether a pavement is a suitable candidate for recycling.

A pavement investigation program, composed of a field survey program, a historical records investigation and a materials testing program, is used to characterize the existing pavement. The field survey program outlines a formal method for evaluating the existing structure and determining its rehabilitation needs. The geometric adequacy, surface condition and structural adequacy of the existing pavement is investigated as part of the field survey program. The historical records investigation is conducted using design, construction and maintenance records to determine what should exist in the field. The materials testing program uses field samples to substantiate or refute the findings of the historical records investigation, as well as to characterize the material properties of the existing subgrade, base and bituminous concrete. The existing pavement is fully characterized, and its rehabilitation needs can be identified when the results of the field survey program, the historical records investigation and the materials testing program are combined. These programs also allow the probable cause of pavement distress or failure to be determined. This determination is used to identify feasible alternatives, both recycling and conventional, that can be used to rehabilitate the pavement. The existing condition of the pavement structure, the distress manifestations that are evident in the existing structure and the distress mechanisms producing the problems are all used to identify rehabilitation alternatives.



No quantitative values have been assigned to any of the decision criteria contained within the Recycling Guidelines. It is anticipated that each transportation agency implementing these guidelines will select appropriate values that would be based upon past experience and local conditions. These then could be used to identify the proper rehabilitation alternative(s) for the extent and severity of pavement distress encountered.

The recycling guidelines also comment on mix design procedures that can be used for the major forms of asphalt pavement recycling. Some procedures are outlined for designing recycled mixes that incorporate additional binder, virgin or salvaged base aggregate and reclaiming agents.

Finally, the recycling guidelines comment on the design of the recycled pavement structure. Procedures are outlined so that the proper thickness of the pavement structure, the recycled layer, as well as the conventional material components, can be selected for anticipated traffic and climatic conditions, as well as for the types of material that will be used.

#### Construction Guidelines

A specific recycling system must be selected in order to implement the rehabilitation alternative generated by the recycling guidelines. A set of construction guidelines was developed to help select the component pieces of equipment that will make up the recycling system. The construction guidelines were presented in Chapter 3 of the interim report "An Investigation of Recycling Bituminous Pavements" by James L.



McKinney (1) and are summarized in this section.

The construction guidelines provide a formal evaluation procedure for the performance of the system and the system components for a specific recycling system. For a specific recycling system, anticipated rates of production, unit costs and unit rates of energy consumption should be calculated. The specific recycling system should be compared to an equivalent conventional system on the basis of life cycle costs, total energy consumption and various environmental considerations.

The construction guidelines also provide a means to analyze the proposed recycling project prior to the start of actual construction. Recycling process variability, project management decisions and potential problem areas are identified for the specific recycling system proposed for use.

Finally, guide specifications for the major forms of recycling are provided in the construction guidelines. The forms of recycling that are covered by the specifications are: heater-planing, hot milling, heater-scarification, cold milling, central plant recycling and in-place recycling. The guide specifications are intended to supplement existing specifications or to provide guidance as to how existing specifications should be modified or revised to account for recycling operation.

#### BEHAVIOR OF COLD-RECYCLED ASPHALT MIXTURES

The following sections present the major findings of the extensive



laboratory investigation of the behavior of col-recycled asphalt pavement mixtures that was conducted by Iida (3) and Tia (2,4).

#### Effect of Added Agent

In an old pavement material, an aggregate piece is surrounded by a hardened layer of binder. During the recycling process, a thin film of virgin binder or softening agent is established. This thin film of virgin binder or softening agent will have rejuvenating effect on the old binder material. The rejuvenating action that takes place is dependent on time, temperature and additional traffic compaction. If too much of the old binder material is "activated" through the rejuvenating action, the mix will have too rich an asphalt content, and problems such as instability and bleeding will occur. (Bleeding is the upward movement of asphalt in a pavement, creating a film of asphalt on the surface). If not enough virgin asphalt or softening agent is added, the mix will be too lean in asphalt content, and it will not have the desirable durability and flexibility.

A laboratory study conducted by Tia (2,4) investigated the effects of different factors on the properties of cold-recycled asphalt mixtures. The factors included the amount and type of added binder, the amount of added moisture, added virgin aggregate, the compactive effort and curing time. A brief summary of this study are reported in the following sections. The reader is directed to interim reports (2,4) when greater detail is required.

The added agents used in the laboratory study include three asphalt emulsions (AE-90, AE-250 & AE-300), three rejuvenating agents





(Reclamite, Mobilsol and Dutrex), an asphalt cement (AC-2.5), a foamed asphalt (made from AC-2.5) and an asphalt cutback (MC-3000).

The results of the study indicate that different added agents can have different rejuvenating effects on the old binder materials. The kind and amount of added binder is the most important factor to both the short-term and long-term behaviors of a recycled mixture.

#### Effect of Compactive Effort

When a virgin binder or rejuvenating agent was added to the aged pavement material, most of the rejuvenating action of the added agent on the old binder was noted to take place during the compaction process. At higher compactive effort, the old binder and the added agent are more effectively blended together. This was evidenced by the higher resilient moduli and Marshall stabilities at the higher compactive efforts. The Hveem R-value, however, was not sensitive to the changes in compactive effort for stable mixes. However, when the binder content was too high, the higher compactive effort produced significantly lower Hveem R-values.

#### Effect of Curing Time

When asphalt emulsion, rejuvenating agent or foamed asphalt was used as the added agent in cold-recycled asphalt mixtures, the binders which underwent the initial softening action during compaction, were observed to increase in stiffness with time. This was caused by the evaporation of water or volatile fractions from the mixture. The resilient moduli, Hveem stabilometer R and S values, and the Marshall sta-



bilities of these mixes generally increased with curing time. Increasing curing time also increased the water resistance of these mixes. When asphalt cement was used as the added binder, it was observed that curing time did not have a significant effect on the properties of the recycled mixes.

When a severely aged asphalt mixture is to be recycled, a large amount of added agent will be required to soften the old binder. In such a case, the initial stiffness and stability of the recycled mix may be too low, and some curing time will be required for the mix to reach its required strength.

#### Effect of Temperature

Testing temperature has a great effect on the measured properties of the cold-recycled mixes. The optimum binder content generally increases as the testing temperature decreases. Thus, an appropriate testing temperature has to be used in the determination of the optimum binder content of the recycled mixes.

#### Effect of Added Virgin Aggregate

The function of added virgin aggregate in recycled asphalt mixtures is to upgrade the deteriorated aggregate. In cold recycling, the added virgin binder tends to adhere to the old pavement material better than to the virgin aggregate. Unless the added virgin aggregate can improve the gradation of the recycled material significantly, virgin aggregate will not improve the performance of a cold-recycled asphalt mix.



### Effect of Added Water

Water is usually added to the cold-recycled mixtures during the mixing process. A small amount of added water (1 - 2%) can facilitate the mixing and the compaction process. However, if too much water is added, the recycled mixture may be too soft initially and a longer curing time is needed for it to reach its required strength.

### Comparison of Mix Performance

Cold-recycled asphalt mixtures are slightly inferior to asphalt concrete in structural performance. The resilient moduli (at 23° C) of the recycled mixes studied range from  $50 \times 10^3$  to  $300 \times 10^3$  psi while that of a standard asphalt concrete is  $450 \times 10^3$  psi. The estimated AASHTO structural layer coefficients of these recycled mixes range from 0.23 to 0.40, while that of asphalt concrete is .44. However, the cold-recycled mixes are comparable to or better than other stabilized base materials such as the cement-treated material or the asphalt emulsion treated mixtures.

The recycled mixes with foamed asphalt added have comparable performance to that of the mixes with asphalt emulsion added. However, slightly more added binder is needed when foamed asphalt is used as the added binder. The three rejuvenating agents used in the study are noted to have strong rejuvenating effects on the older binder materials. The limited study on the use of the asphalt cement AC-2.5 and the asphalt cutback MC-3000 indicates that difficulties with good mixing and coating might be encountered when these two materials are used as added binders



to cold-recycled mixes.

When a mildly aged pavement material is to be recycled, an asphalt emulsion (such as AE-150) can be used as the added binder. When a severely aged pavement material is to be recycled, a rejuvenating agent (such as Reclamite) can be used as the added agent, together with the proper amount of added asphalt emulsion to coat the added virgin aggregate.

#### DESIGN OF COLD-RECYCLED ASPHALT MIXTURES

The most important objective of the laboratory study is to provide

guidelines for the design of cold-recycled asphalt mixtures from the understanding of the behavior of these mixes. The following sections present the conclusions made on the use of the blending curve and the gyratory testing machine, and a recommended design procedure for cold-recycled asphalt mixtures.

##### Blending Curve

A blending curve (3) shows the relationship between the concentration of the softening agent and the viscosity of the blend consisting of the old asphaltic binder and the softening agent. It is usually used to determine the amount of added agent to obtain a target viscosity of the blend. The experimental results indicate that a functional relationship exists between the concentration of the added agent and the viscosity of the blend. The viscosity of the blend plays an important role in affecting the properties of the recycled mixture. However, the target





viscosity does not always give the optimum mixture property. Therefore, the viscosity curve can only be used to give a rough estimate of the amount of added agent.

### Gyratory Testing Machine

The gyratory testing machine is commonly used for compacting and testing hot bituminous mixtures. The experimental results indicate that the gyratory testing procedure (ASTM D-3387) can be used to determine the optimum binder content of a cold-recycled mixture. However, the gyratory indices obtained can not be used to estimate the resilient modulus or the Marshall stability of the mix.

The gyratory machine is shown to give consistent compactive efforts and can be used to compact cold-recycled asphalt mixtures at various levels.

### Recommended Mix Design Procedure

The main purpose of this study was to investigate a method that concerning proportioning of ingredients in cold recycled asphalt paving mixtures. Based on the findings from this study, the following design

1. An extraction test should be performed on the old pavement material to be recycled. The amount and gradation of virgin aggregate to be added can be determined from the gradation of the recovered aggregate.
2. The gyratory machine can be used to effectively and efficiently determine the optimum amount of virgin binder or rejuvenating



agent to be added. The recycled mixes with various binder contents are to be compacted with the gyratory machine for 60 revolutions at 200 psi (2.38 MPa) and the gyratory indices (GSI and GEPI) are to be obtained from the gyrograph. The optimum binder content is the maximum binder content above which the gyratory stability index (GSI) and the gyratory elasto-plastic index (GEPI) will increase appreciably.

3. The recycled mixes of optimum binder contents can be characterized by means of the resilient modulus, Hveem R-value and Marshall tests. Since compactive effort and curing time can greatly effect the properties of the recycled mixes, the complete ranges of compactive effort and curing time should be considered for material characterization. The two recommended compactive efforts are 20 revolutions at 200 psi (to simulate initial construction condition) and 60 revolutions at 200 psi (to simulate ultimate traffic compaction). The two recommended curing times are 1 day curing and ultimate curing (by means of 24-hour heating at 60°C).
4. The Water Sensitivity Test as modified from the suggested Asphalt Institute method can be used to determine the effect of water on the recycled mixes.
5. The choice of virgin binder or rejuvenating agent to be used can be determined from the comparison of the material properties of the various recycled mixes considered and from the comparison of their costs.



The detailed laboratory procedures for the preparation of recycled mixtures and the various tests mentioned above can be found in Chapter 5 of the interim report "Characterization of Cold- Recycled Asphalt Mixtures" by Mang Tia (4).

#### LONG TERM EFFECTS OF SOFTENING AGENTS ON RECYCLED MIXTURES

A study conducted by Iida (3) dealt with the long-term effects of softening agents on recycled mixtures produced in a cold process. A reader desiring more detailed information is directed to the interim report (3) listed in the references at the end of this report.

First, a conceptual diagram of the long-term behavior of recycled mixtures was proposed in which the concept of the viscosity of mixture was introduced. The reaction of a softening agent with an old asphalt was explained schematically and the existence of thin layers with different viscosities was predicted.

Next, literature was reviewed and it was found that while recycling was becoming widely used there still were many questions that were unsolved. In general, there seems to be two concepts in the recycling practice; one of them is that asphalts are to be added to old mixtures to reunite the pulverized old materials, and the second is that the consistency of the old asphalt is to be reduced to a certain level by adding commercially available rejuvenating agents. Design procedures were different in the two concepts. The first usually employed a conventional mix design method, while the second used a blending curve.



Based upon the conceptual model and the literature review, an experiment was set up to observe long-term behavior of recycled mixtures. Softening agents, AE-150, AE-300, AC-2.5 and two rejuvenating agents, Reclamite and Mobilsol were used. As an index of the long-term behavior it was decided to utilize creep parameters as obtained from a creep test and the Burgers Model, and some basic studies were made to observe creep behavior of mixtures.

In the course of the experiment, blending curves for various agents used in this study were drawn and it was discovered that a functional relationship existed between the concentration of the agents and the viscosity of the blends irrespective of the type of agents used.

The initial and long-term behavior of recycled mixtures were reported. The effectiveness of the agents was discussed from the standpoint of the mix design using the initial properties. The long-term properties were compared among the specimens with different agents by means of Burgers Model parameters and statistical procedures. The viscosity of mixture,  $\eta_3$ , and the calculated viscosity of the blend of oxidized asphalt and softening agent were shown to be strongly related. During the observations, it was found that some specimens showed an initial softening effect at early ages. A conceptual model was developed using the rate of change in  $\eta_3$  to explain this effect. Also, the relationship between the Hveem Stability R and S and the creep parameters was discussed. Finally the results obtained in the accelerated weathering test were presented. Comparison of these with the results for specimens aged at room temperature showed that the accelerated test procedure produces a different reaction inside the mixture, and a direct





comparison of the two weathering procedures is difficult.

### The Usefulness of the Softening Agents

The usefulness of the softening agents was examined from the standpoint of initial mixture properties, and the following points are presented:

1. When the original mixtures to be recycled were mildly weathered, AE-150 produced mixtures that could be used even as a surface course material.
2. When the original mixtures were strongly oxidized, AE-150 AE-300, Reclamite and Mobilsol produced mixtures that could be used as base course material; however, an initial softening effect may take place which could affect early stability of the mixture.
3. AC-2.5 is difficult to use a recycling agent for heavily oxidized materials. AC-2.5 seems to have the effect of only binding the old oxidized materials together.
4. The softening agents might be used to produce a surface course material with the heavily oxidized mixtures, when the virgin aggregate and virgin asphalt sufficient to cover the virgin aggregate and to soften the old mixtures are added.

### Blending Curve



1. Blending curves were used to determine the amounts of Mobilsol and Reclamite required to obtain a target viscosity of the blend. The target viscosity, however, did not always give a favorable mixture property, because the target viscosity was arbitrarily determined. Therefore it is dangerous to determine the amount of the agents solely by the blending curve; a mix design procedure is required.
2. The experimental results indicated that a functional relationship existed between the concentration of an agent and the blend viscosity irrespective of the type of the agents used. This indicates that there is no intrinsic difference in the agents with respect to the function to reduce the viscosity of the old asphalt.

#### Initial Softening Effect

Based upon a conceptual model using the film thickness and relative magnitudes of the viscosities of the old asphalt and the agent, the following summary is made:

1. When the difference in viscosities is large and the dispersing power of the agent is small, an initial softening effect was present.
2. When the difference in viscosities is small, the initial softening effect may not occur.
3. Commercially available rejuvenating agents used in this study, show a rapid reaction with the old asphalt and the initial



softening effect did not occur.

### The Long-Term Properties

The comparison of the long-term properties using the Burgers Model and Statistical procedures produced the following results:

1. The calculated viscosity of the blend was found to play an important role in producing mixture properties. This factor was especially conspicuous in the retardation time  $\tau$  and the mixture viscosity  $\eta_3$ . This factor becomes more important as the age progresses, and the blend becomes more homogeneous.
2. AE-150 and the two rejuvenating agents used in this study had a tendency to increase  $\eta_3$  and lower  $\tau$ , while AC-2.5 does not. A high value of  $\eta_3$  is favorable because the permanent deformation induced by load is small. Attention should be paid, however, to the behavior of  $\eta_3$  when AE-150 and AE-300 are used. Usually  $\eta_3$  is considered to be positively correlated to the viscosity of asphalt in the mixture. The results with  $\eta_3$  indicate a negative correlation for these materials, which may be due to their specific high-float nature. Furthermore, some specimens with AE-300 and Reclamite developed a decrease in  $\eta_3$  after two months, which should also be heeded.
3. Other parameters than  $\tau$  and  $\eta_3$  seem to be affected by the blend viscosity, but other factors may have stronger effects on them.  $E_1$ , the modulus of elasticity in the Maxwell Model is strongly affected by the calculated blend viscosity at the initial obser-



vation, but the effect seems to be weakened in later days.

### The Creep Test and Viscoelasticity

1. The creep test employed in this study proved to be very effective in describing mixture properties. The creep compliance is not useful when it is used alone, however. Viscoelastic analysis must be included and the creep parameters must be computed.
2. The Hveem Stability R and S were interpreted by the theory of viscoelasticity using the creep parameters. It was found that S values determined at the standard temperature of 140 F (60 C) are correlated with viscoelastic models, while R values and S values measured at room temperature were related to the modulus of elasticity.

### Miscellaneous

1. With respect to the properties of old mixtures, two points must be kept in mind. First, the old mixtures, especially heavily oxidized ones, tend to produce large chunks, which may cause insufficient dispersion of softening agent. Second, when virgin aggregate is introduced to the old mixtures, migration of the agent may take place from the virgin aggregate to old mixtures, and this causes insufficient coating on the virgin aggregate.
2. A conceptual model that the highly oxidized portion of asphalt may be inert and considered as part of the aggregate was not proved.





3. The conceptual model given in Figure 1, Chapter 1, (3) indicates the possibility of establishing maximum and minimum limits for  $\eta_3$ . This could not be accomplished in this study, partially because the particular character of AE-150 raised the value of  $\eta_3$  even when the blend viscosity was lowered.
4. The accelerated weathering test procedure used in this study did not produce the same results as those that occurred with time at ambient temperature.

### Conclusions

From the results of this study, the following conclusions are presented. Although they are thought to be appropriate over a wide range of application, it must be borne in mind that these conclusions are known to be valid only for the materials and methods used in this study.

1. Recycling by a cold process using emulsified asphalts or commercially available rejuvenating agents is possible. When the old mixtures to be recycled contain mildly weathered asphalt, recycling may produce even a surface course material. When the asphalt of the old mixtures is strongly oxidized, the resultant mixture may be used as a base course material, but instability in the mixture may take place when the difference in viscosities between the agent and the old asphalt is comparatively large and the dispersing ability of the agent is weak.
2. A soft grade of asphalt cement can reduce the viscosity of old



asphalt cement, but its effectiveness as a recycling agent is open to question.

3. With respect to the long-term properties of cold recycled mixtures, the viscosity of the blend of the old asphalt and the agent changes with time and therefore affects the properties of the mixtures as the age progresses.
4. The creep test utilizing viscoelastic principles can be used to measure the long-term behavior of cold recycled mixtures.
5. An accelerated weathering procedure utilizing elevated temperature affects specimens in a different way than that produced by non-accelerated weathering utilizing ambient conditions.



## LIST OF REFERENCES

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